Synthesis Imaging Workshop

Error recognition

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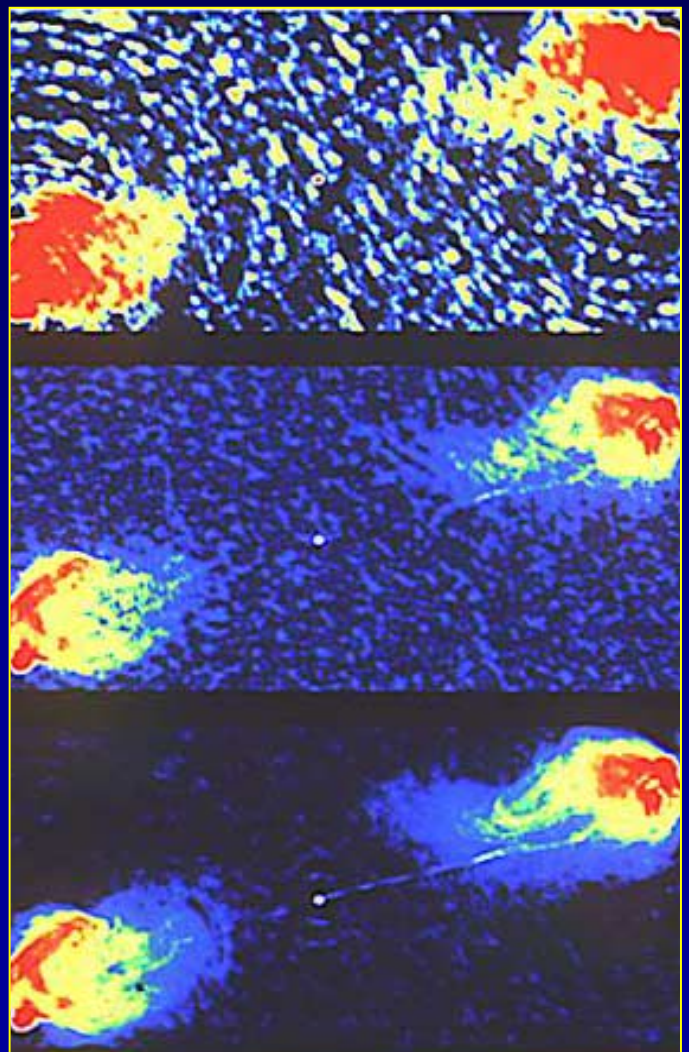
Narrabri, 14 May 2003

Summary

- Follows Chapter 10 “Error Recognition” in NRAO Synthesis Workshop closely
- Educational
  - Use of basic concepts and analogies
  - Fourier transform practice
- Practical information for diagnosing errors
- Diagnostic tools

"Well, here's your problem, Mr. Schueler."

Cygnus A



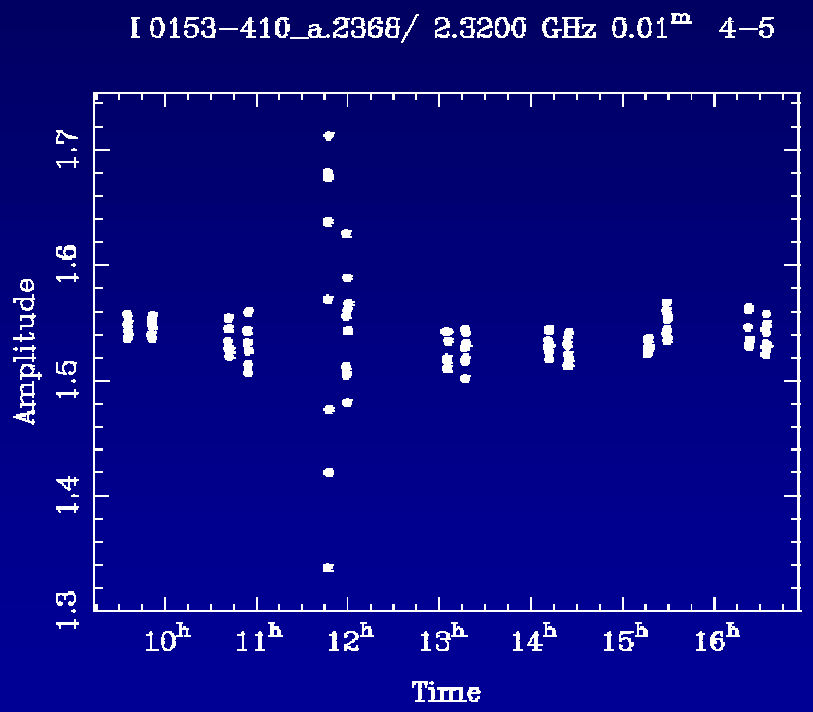
- Raw data
  - VLA continuum
- Deconvolution
  - Uses non-linear algorithms to correcting for errors due to missing information in the Fourier domain
- Self Calibration
  - Uses the *corrupted* image of the object to remove antenna based gain errors

Image or Aperture Plane?

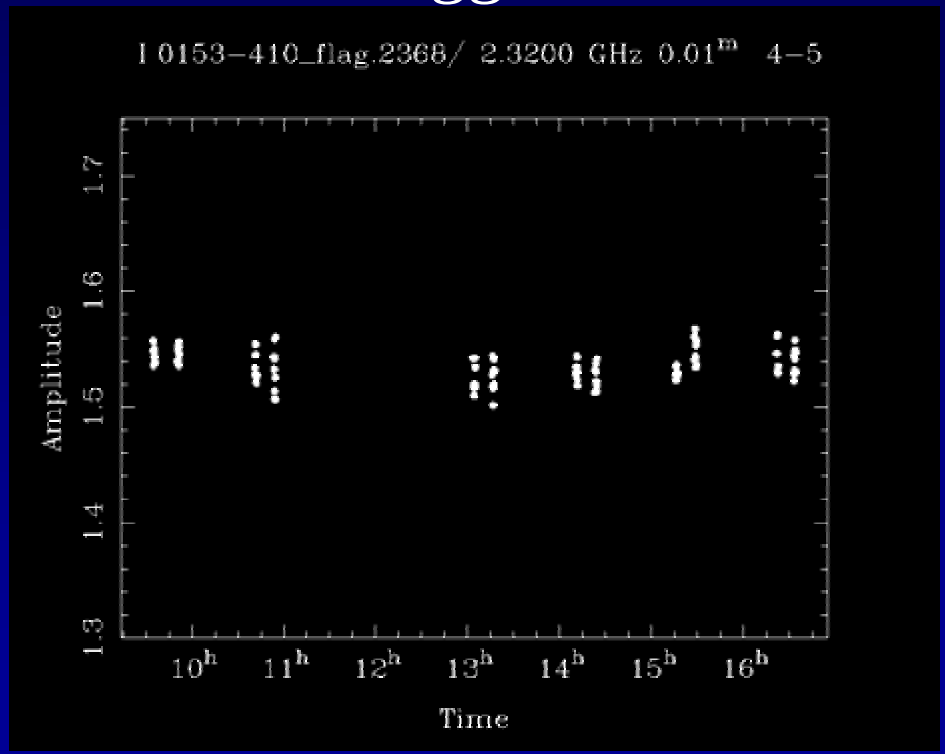
- Most errors occur in the measurements (aperture plane) but effect the science in the image plane
- Errors obey Fourier transform relations:
  - narrow features transform to wide features (and visa versa)
  - symmetries important - real/imag, odd/even, point/line/ring
- Some errors more obvious in particular domain
  - switch between image and uv planes
- The transform of a serious error may not be serious!
  - effects are diluted by the number of other samples

Bad Scan - Visibilities:

Unflagged:



Flagged:

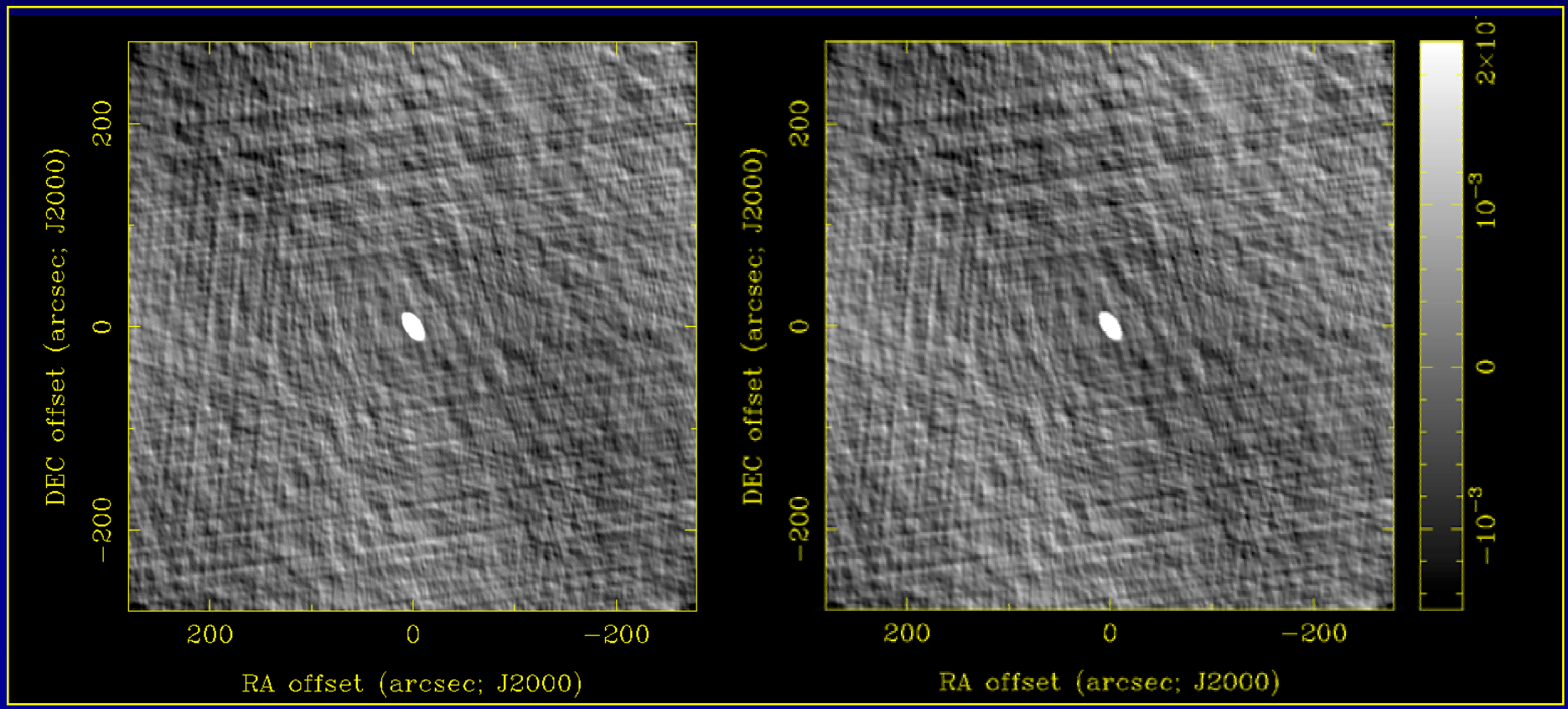


Only two scans on 1/15 baselines affected.

Bad Scan - Images:

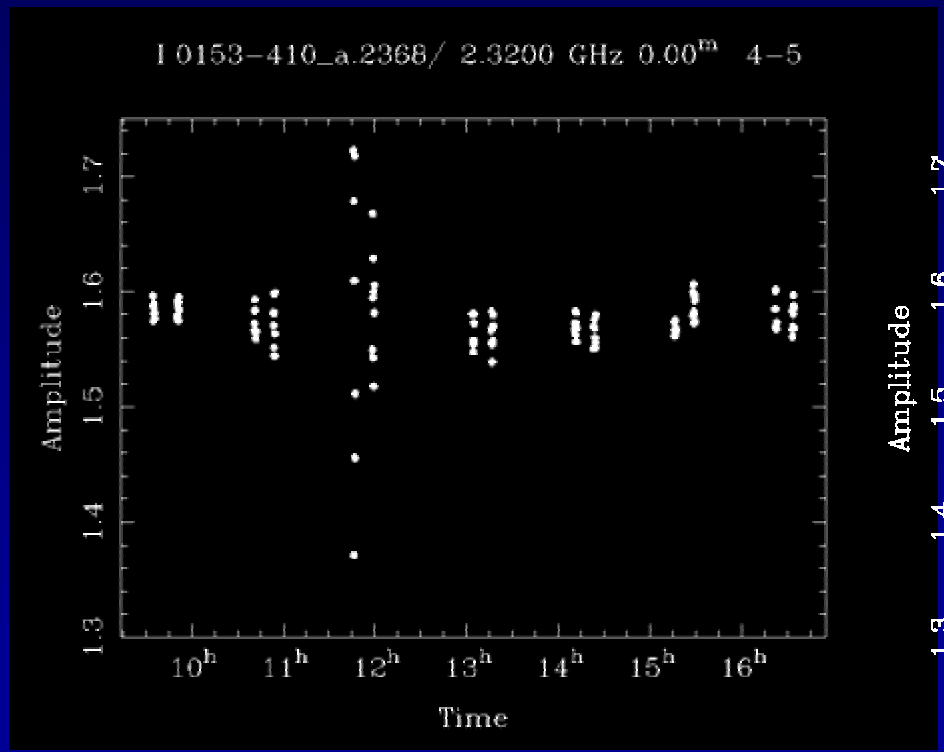
Unflagged:

Flagged:

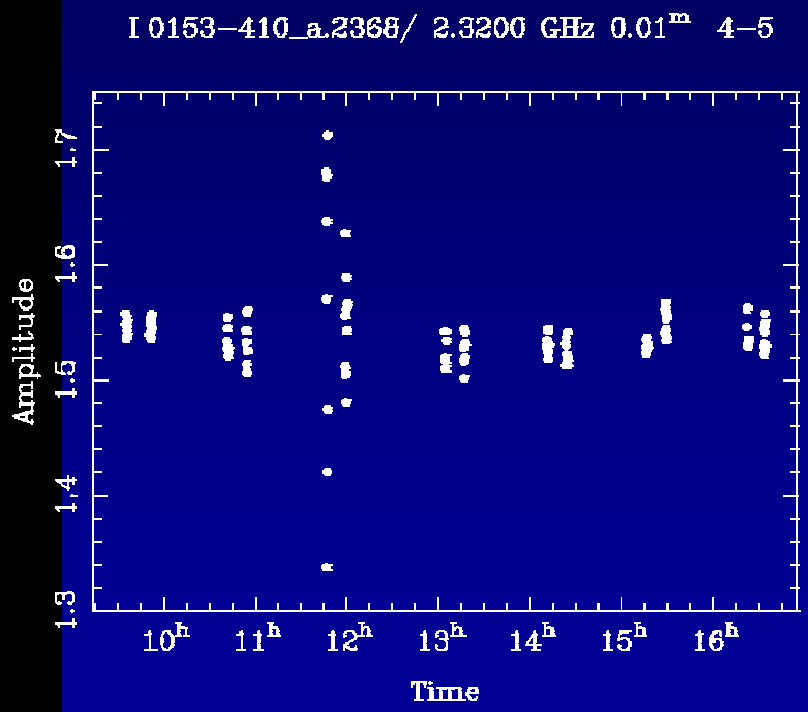


Bad Gain - Visibilities:

2.5% Gain error one ant:



Properly Calibrated:

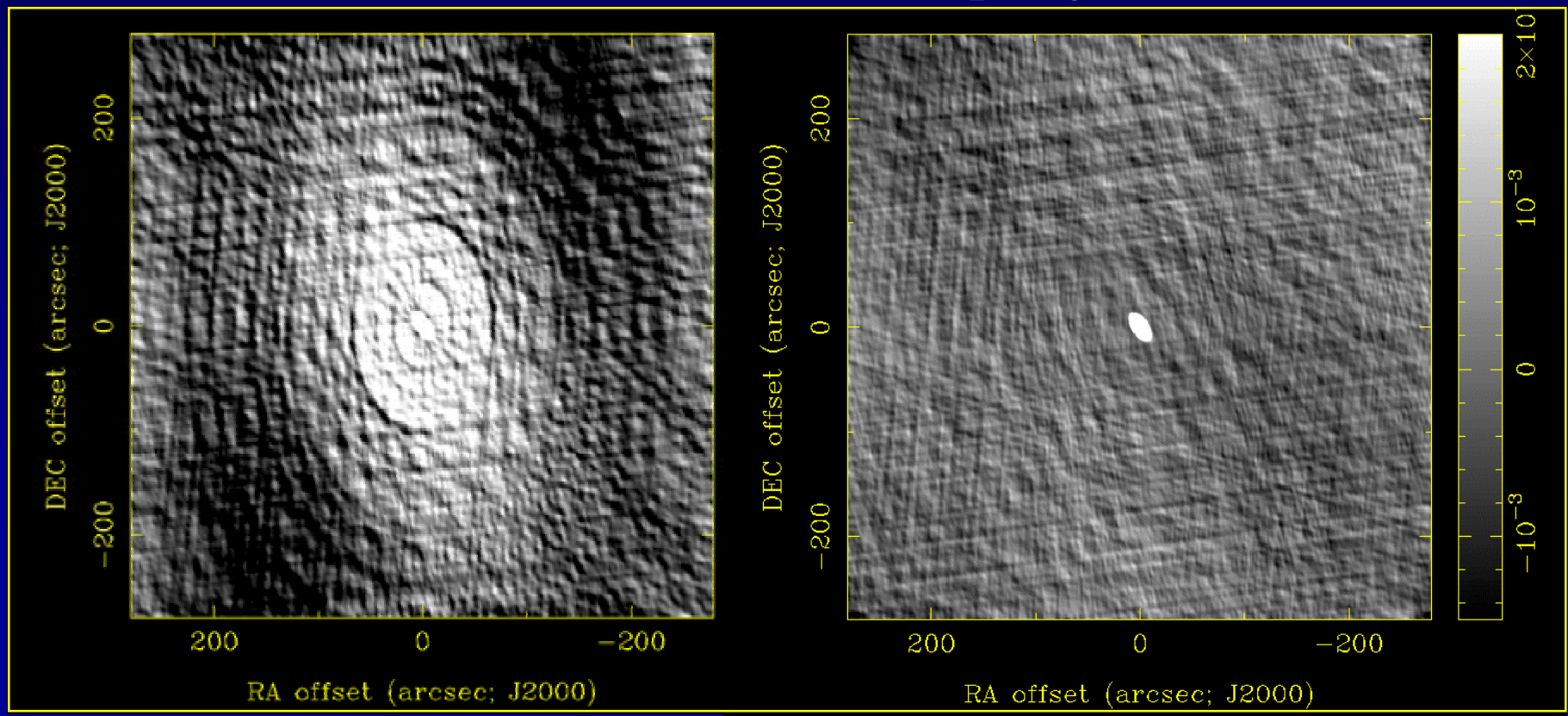


Gain error affects all visibilities on 5/15 baselines

Bad Gain - Visibilities:

2.5% Gain error:

Properly Calibrated:



The 2D Fourier Transform

- x,y (radians) in tangent plane relative to phase center
- spatial frequency u,v (wavelengths)
- adopt the sign convention of Bracewell:

$$I(x,y) \quad \Leftrightarrow \quad \bar{I}(u,v)$$

$$I(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} du\,dv\,\bar{I}(u,v)\,e^{2\pi i(ux+vy)}$$

$$\bar{I}(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dx\,dy\,I(x,y)\,e^{-2\pi i(ux+vy)}$$

The Fourier Theorems

- shift in one domain is a phase gradient in the other

$$F(x - x_0, y - y_0) \quad \Leftrightarrow \quad e^{-2\pi i (ux_0 + vy_0)} \bar{F}(u, v)$$

- multiplication in one domain is convolution in the other

$$F * G(x, y) \quad \Leftrightarrow \quad \bar{F}\,\bar{G}(u, v)$$

$$F\,G(x, y) \quad \Leftrightarrow \quad \bar{F} * \bar{G}(u, v)$$

$$F * G(x, y) \quad = \quad \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(x', y')\, G(x - x', y - y')\, dx'\, dy'$$

Fourier Symmetries

- symmetries determined by Fourier kernel
- $\exp(i \varphi) = \cos \varphi + i \sin \varphi$
  - Real ⇔ Real Even + Imag Odd
  - Imag ⇔ Real Odd + Imag Even
  - Real & Even ⇔ Real & Even
  - Real & Odd ⇔ Imag & Odd
  - Even ⇔ Even Odd ⇔ Odd

→ **image errors with odd symmetry or asymmetric often due to phase errors**

- real sky brightness ⇔ Hermitian uv plane
  - complex conjugate of visibility used for inverse baseline

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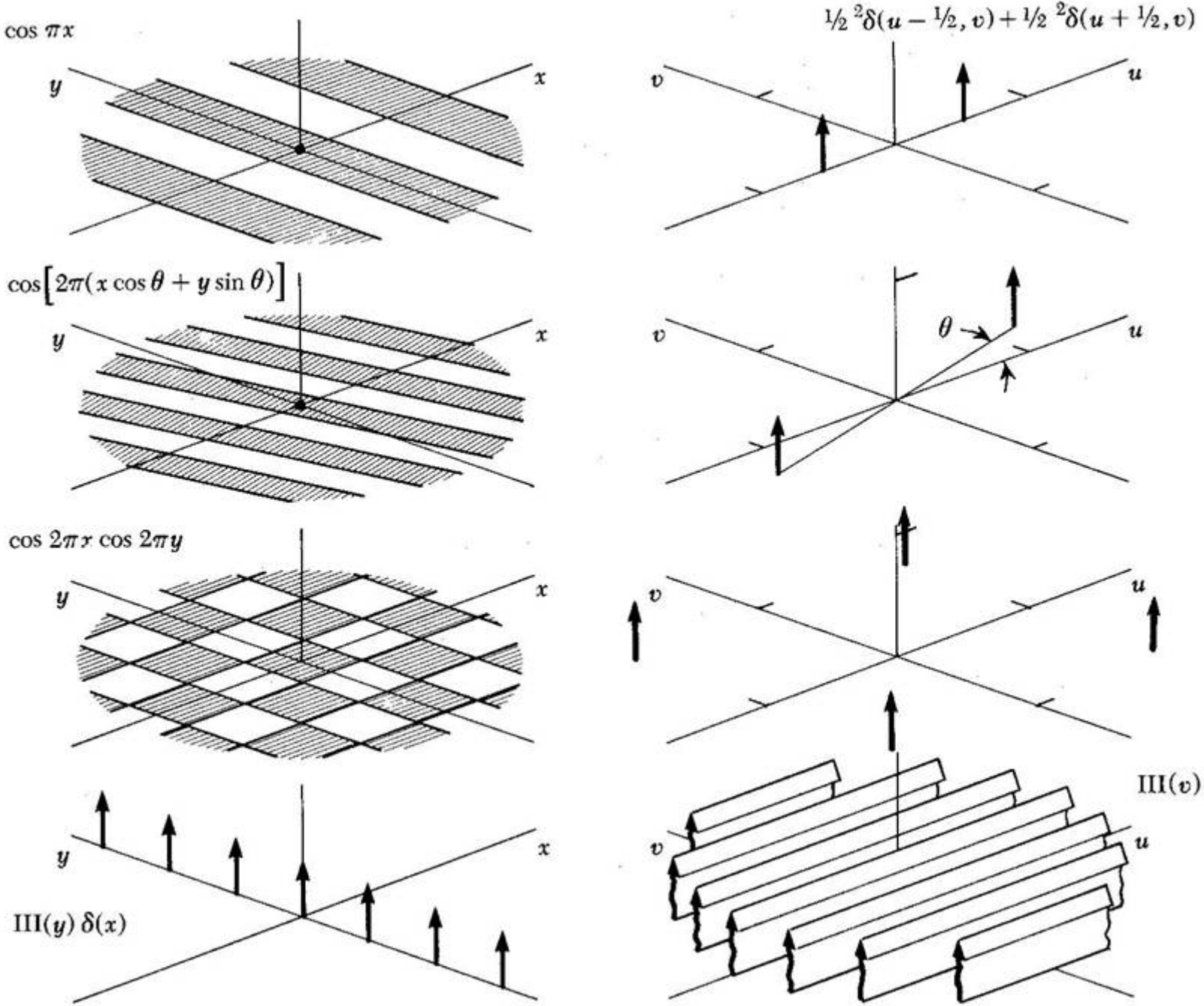
  - Real & Odd ⇔ Imag & Odd

Symmetric image errors are often due to amplitude errors

image errors with odd symmetry or asymmetric often due to phase errors



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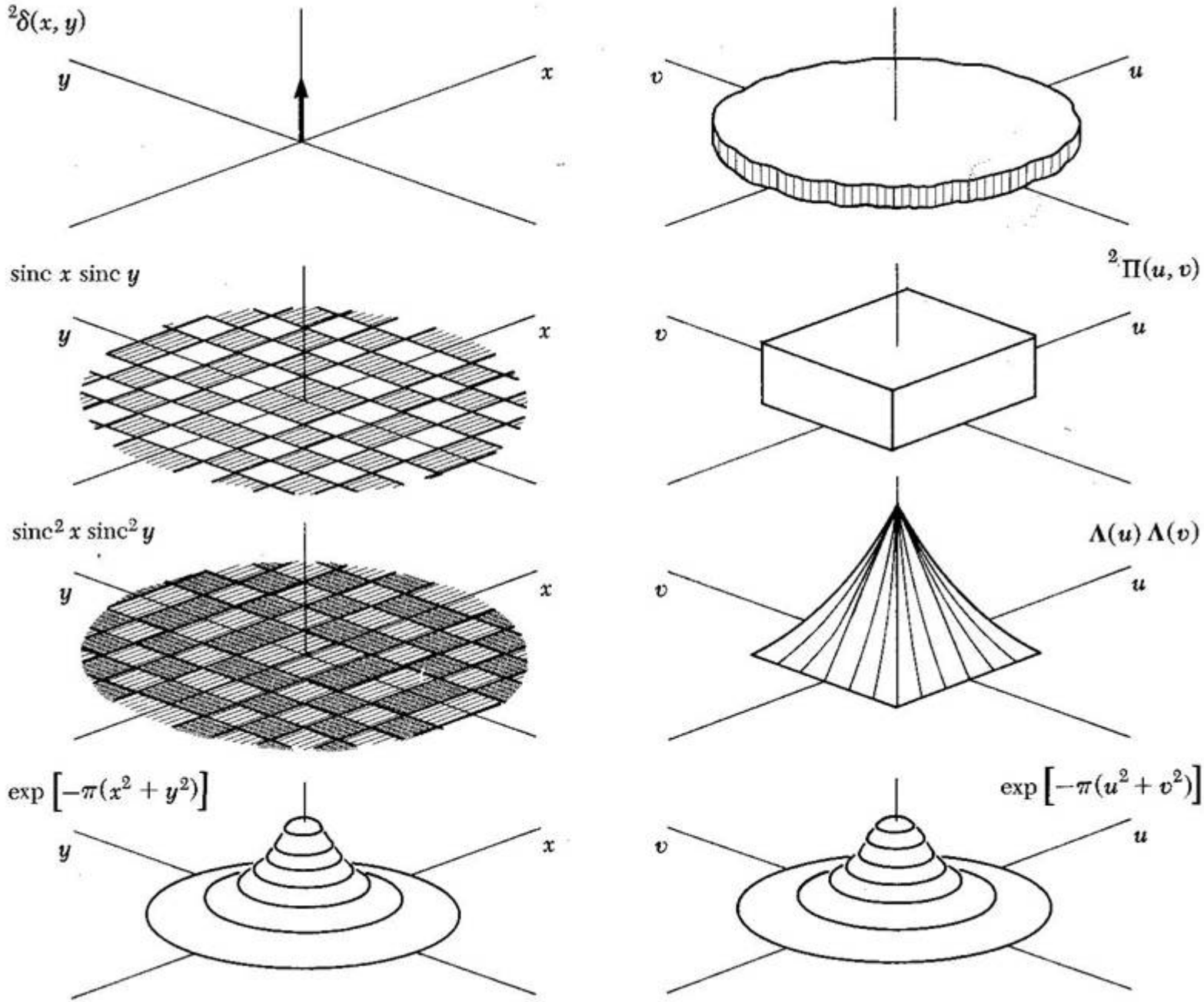

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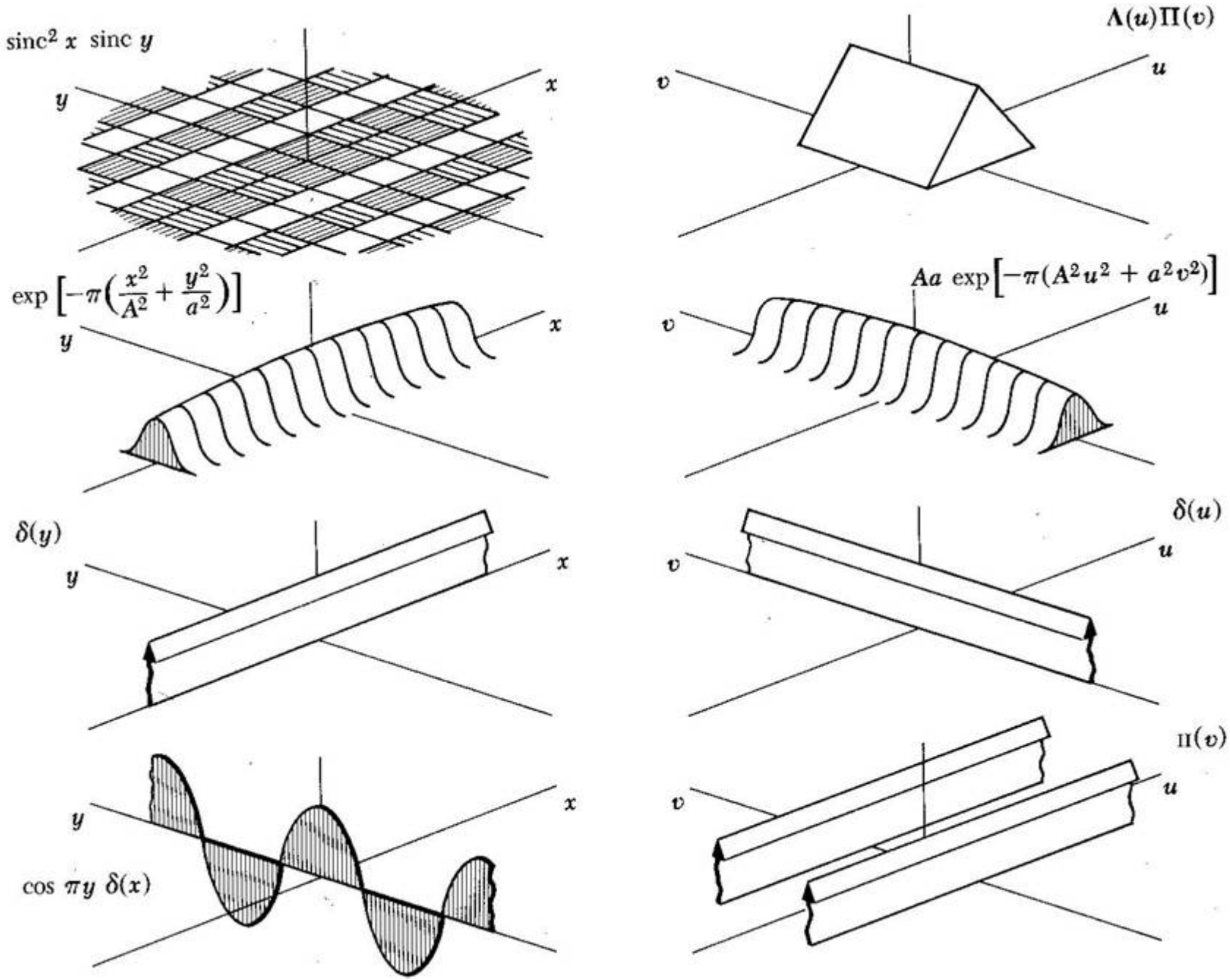

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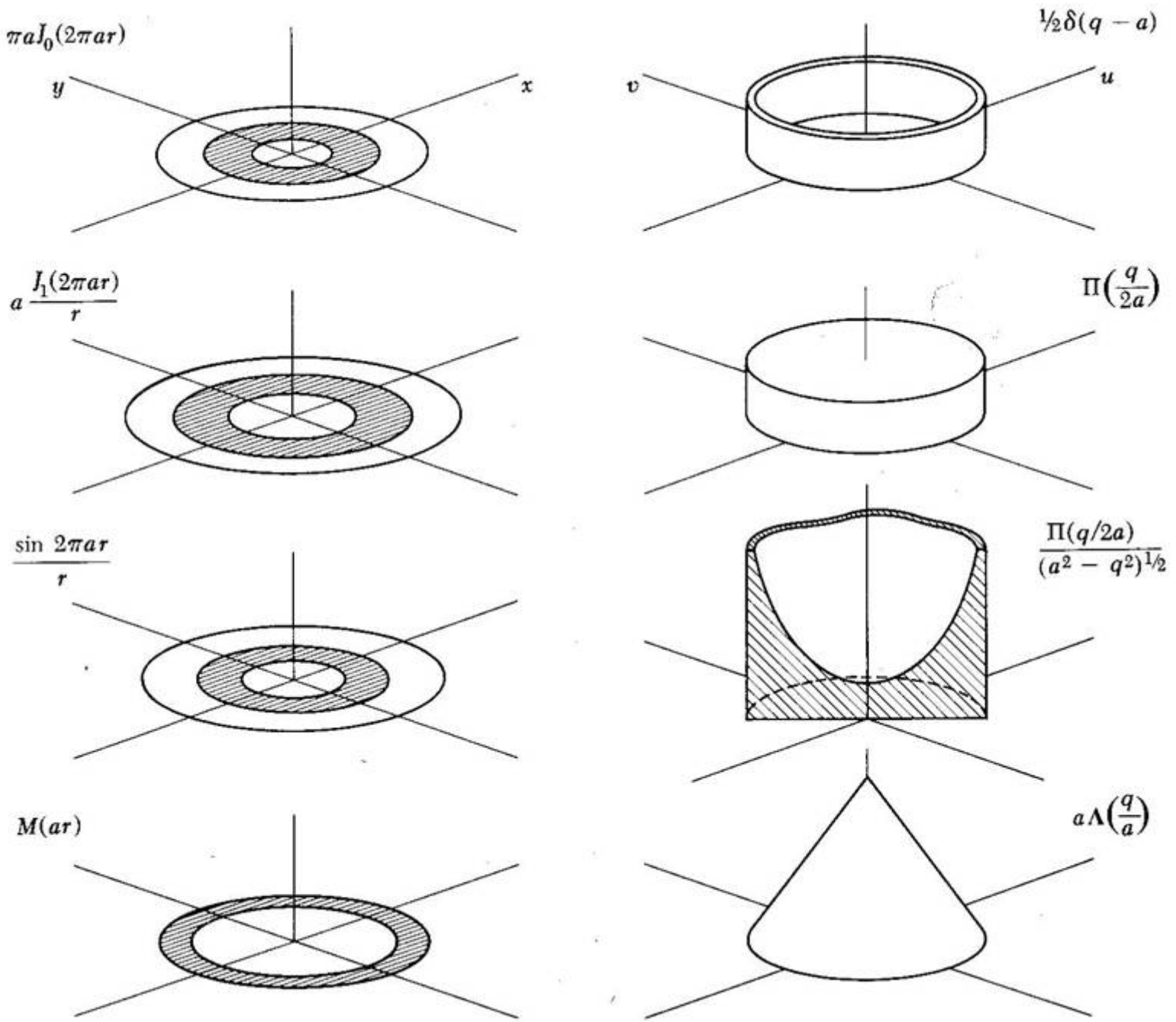

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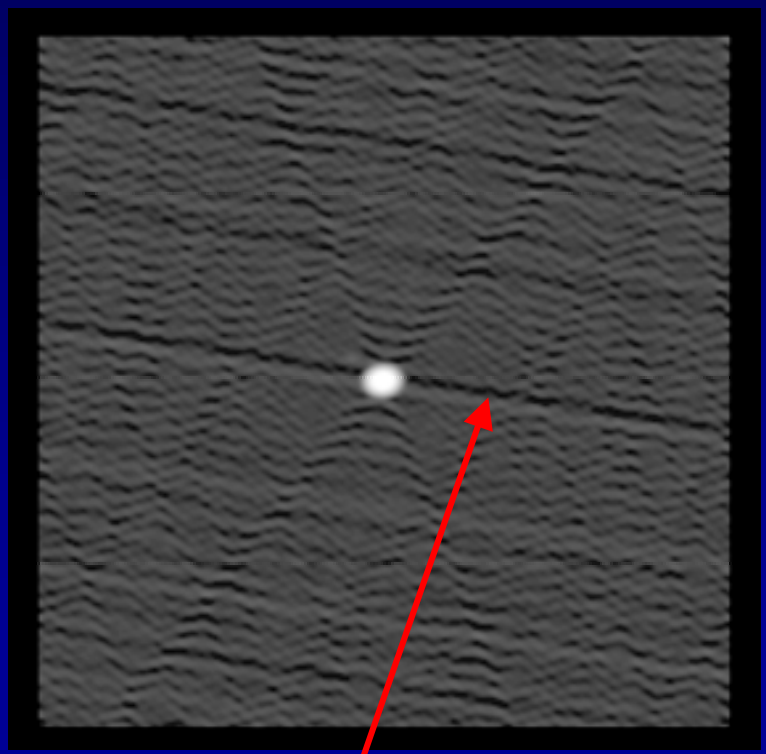
Error Diagnosis

- amplitude or phase errors:
  - phase errors usually asymmetric or odd symmetry
  - amplitude errors usually symmetric (even)
- short duration errors:
  - localized in uv plane ⇔distributed in image plane
  - narrow ⇔ extended orthogonal direction in image
- long timescale errors:
  - ridge in uv plane ⇔ corrugations in image
  - ring in uv plane ⇔ concentric “Bessel” rings in image

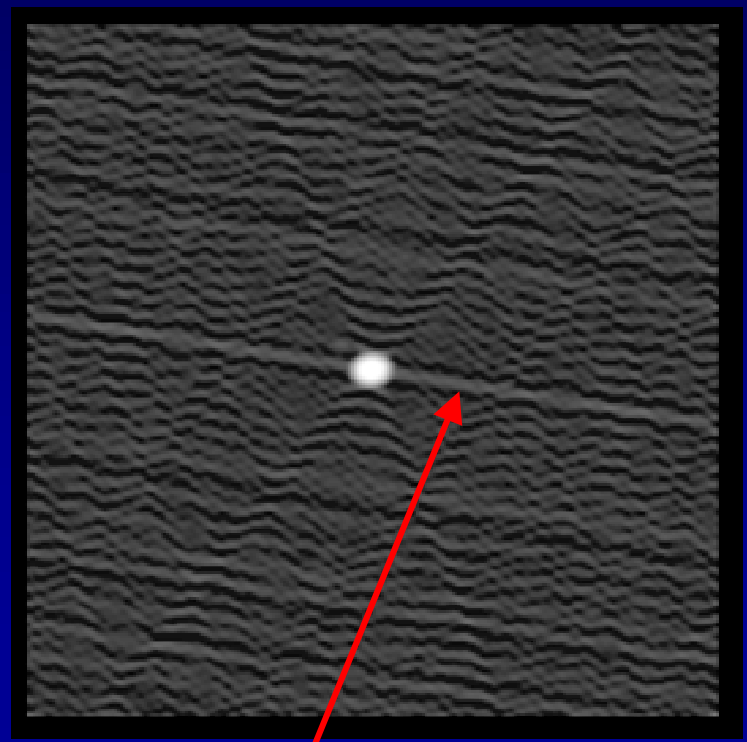
Example Gain Error - 2

10 deg phase error 1 ant 1 time
rms 0.49 mJy



anti-symmetric ridges

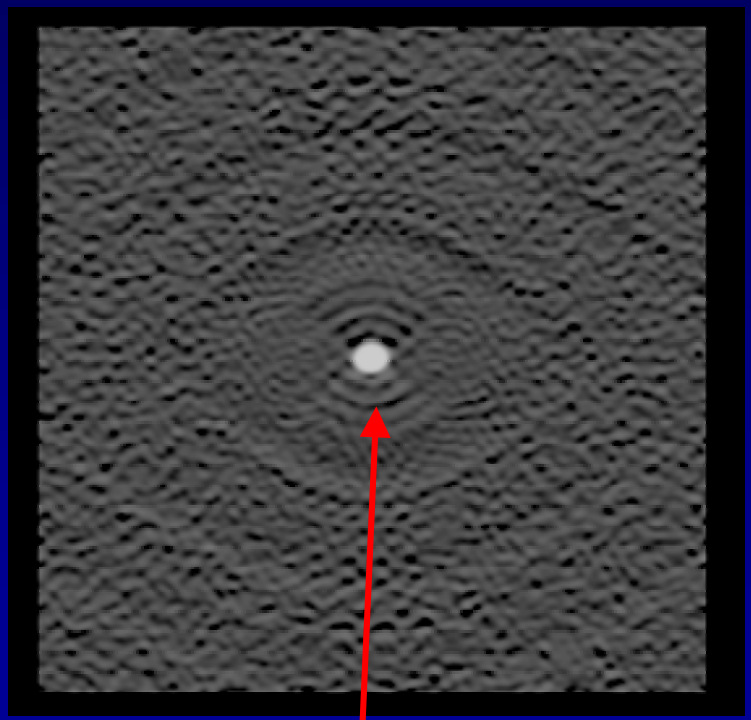
20% amp error 1 ant 1 time
rms 0.56 mJy



symmetric ridges

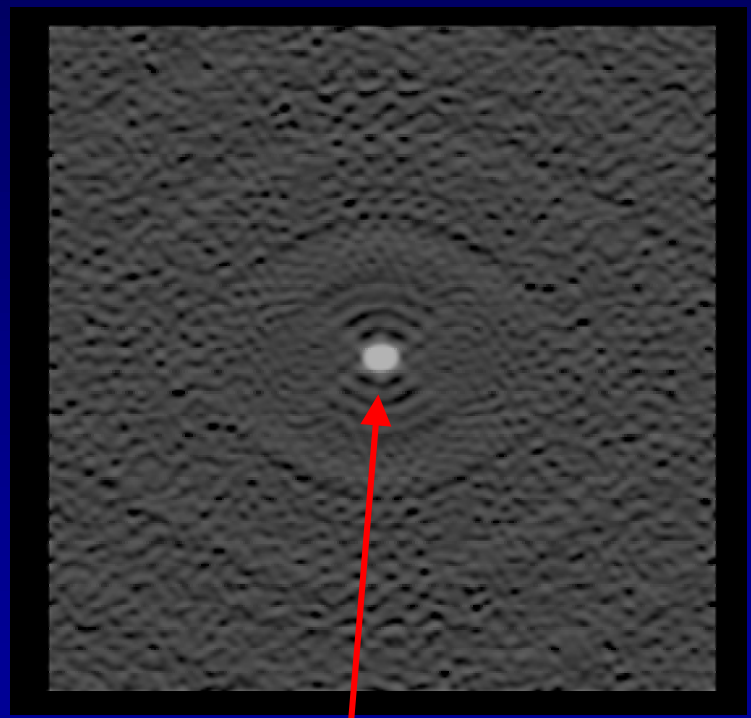
Example Gain Error - 3

10 deg phase error 1 ant all times
rms 2.0 mJy



rings – odd symmetry

20% amp error 1 ant all times
rms 2.3 mJy



rings – even symmetry

Additive

$$V + \epsilon \quad \Leftrightarrow \quad I + \mathcal{F}\epsilon$$

- some errors *add to* visibilities
  - additive in conjugate plane
  - examples: noise, confusion, interference, cross-talk, variable source, source outside field (eg sun)

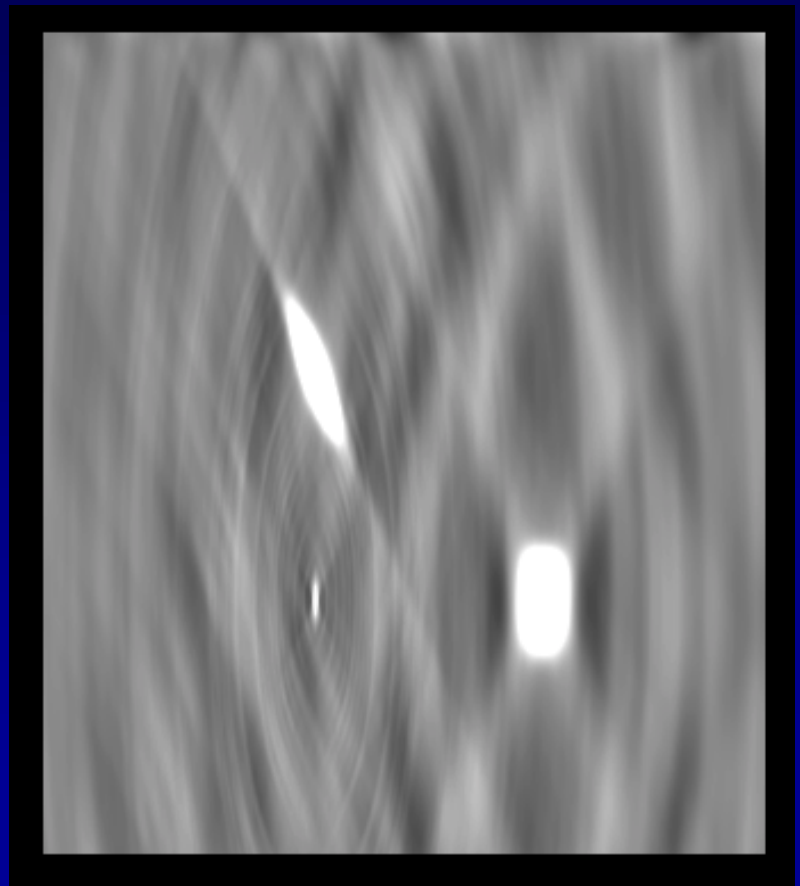
Multiplicative

$$V\epsilon \Leftrightarrow I * \mathcal{F}\epsilon \qquad V * \epsilon \Leftrightarrow I\mathcal{F}\epsilon$$

- others *multiply* or *convolve* visibilities
  - multiplication ⇔ convolution in conjugate planes
  - examples - multiplicative: sampling, gain errors, atmosphere, missing short spacings
  - examples – convolution: primary beam, gridding

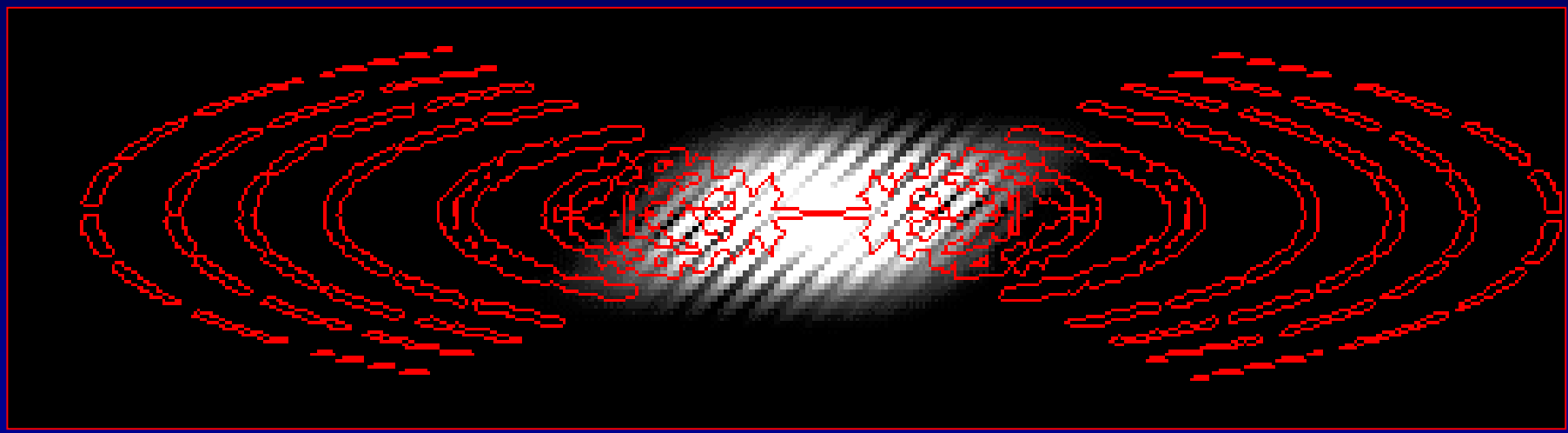
Inadequate UV coverage:

- CLEAN
  - 3 clean boxes
  - 1000 iterations
- MAXEN
  - 3 boxes
  - 30 iterations



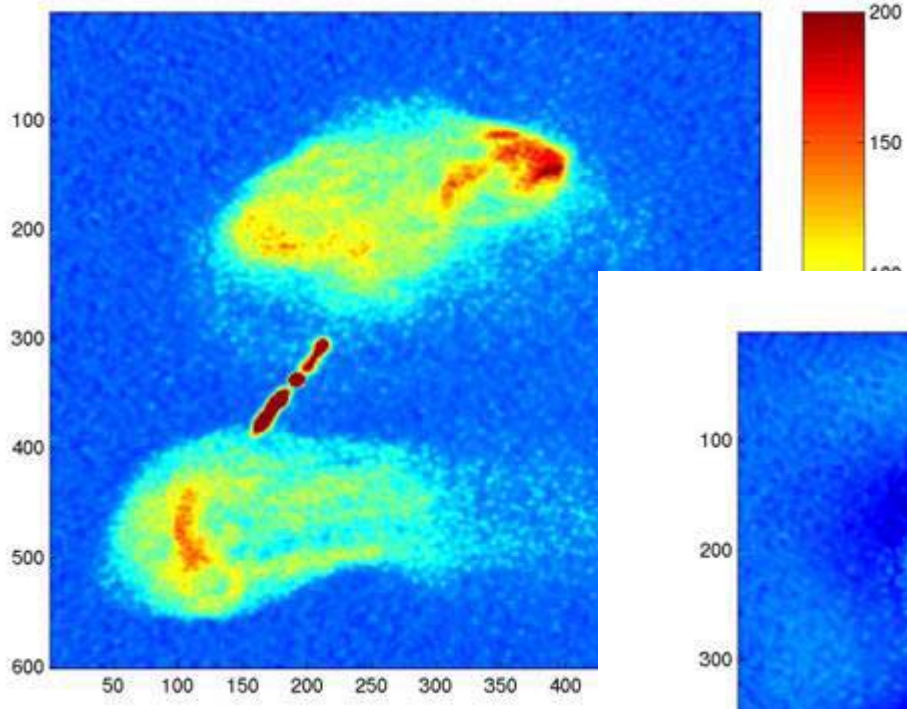
Recognizing Poor UV Coverage:

- Fourier Transform the Source Model and Beam!

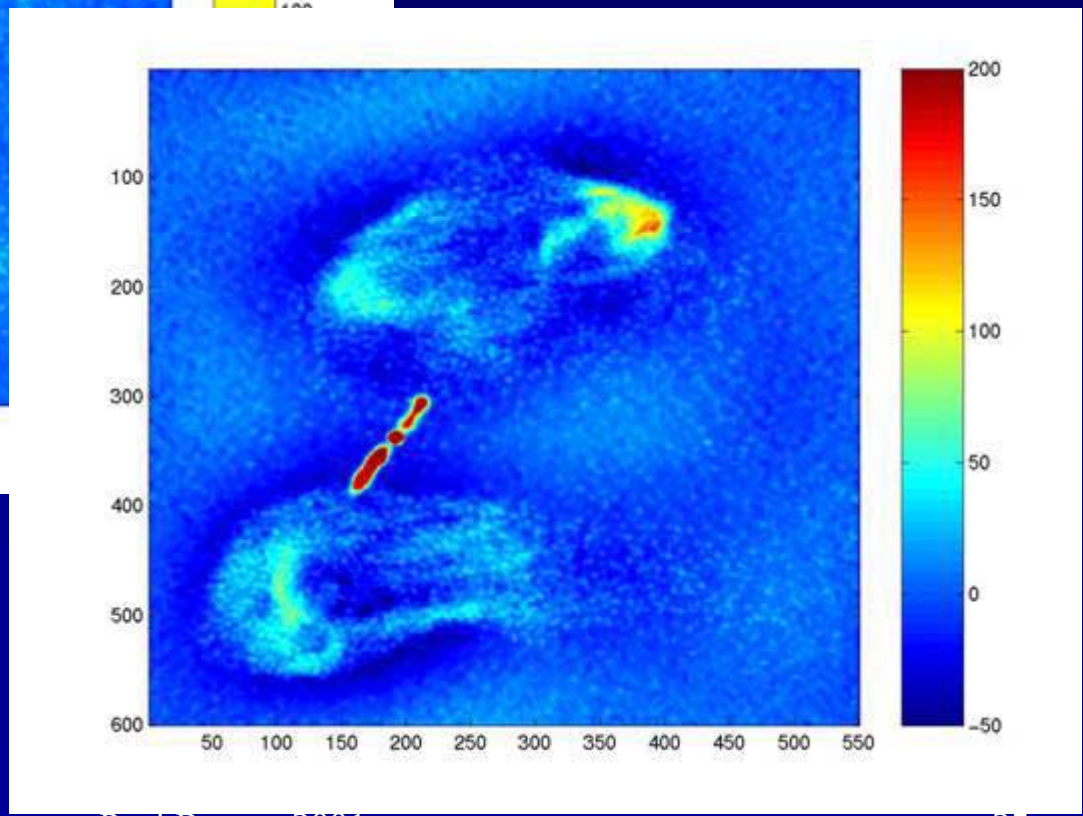


- Use different array configuration.
- Different frequency, if possible.
- North-spur, when available.

Effect of missing short baselines



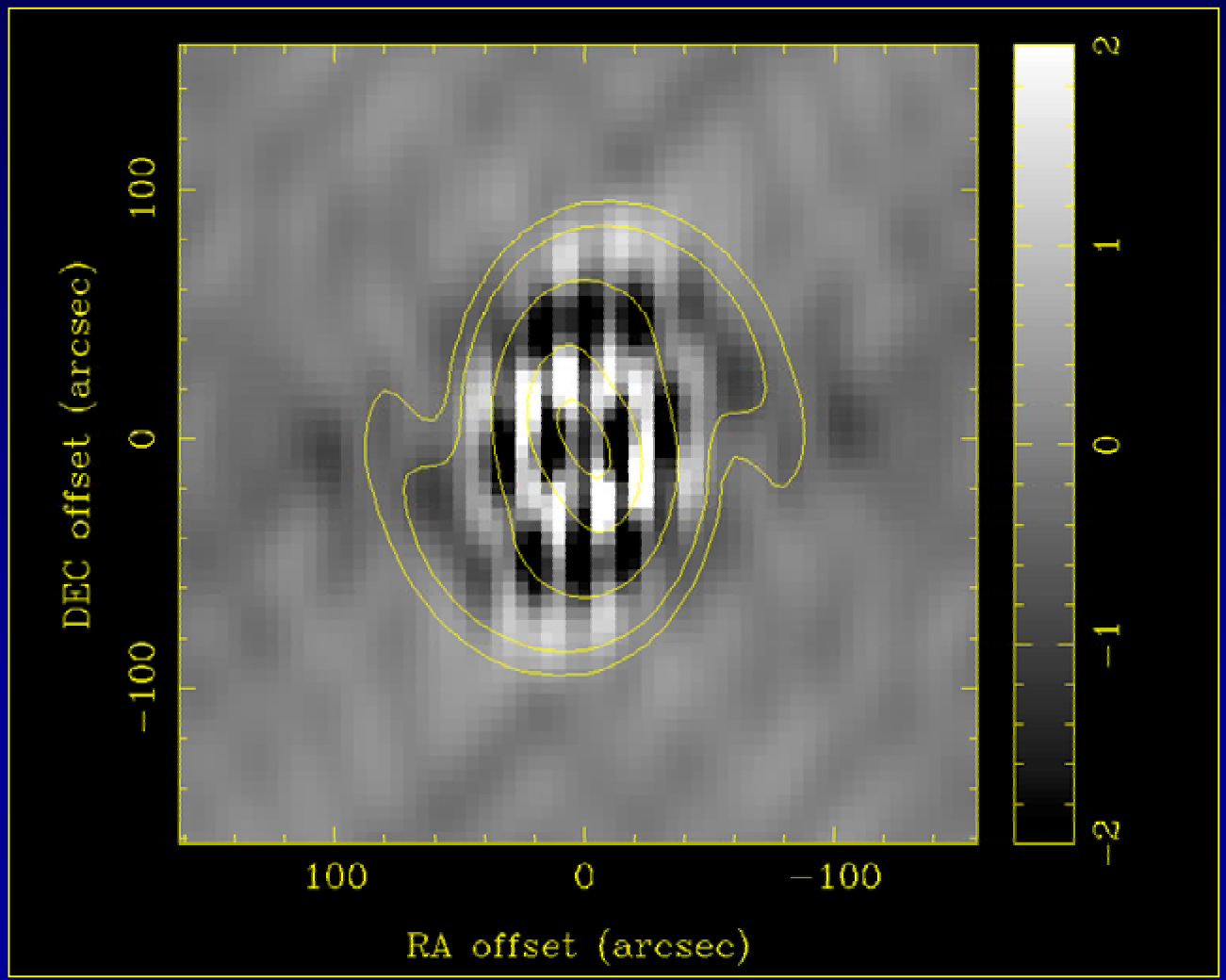
No short baselines →



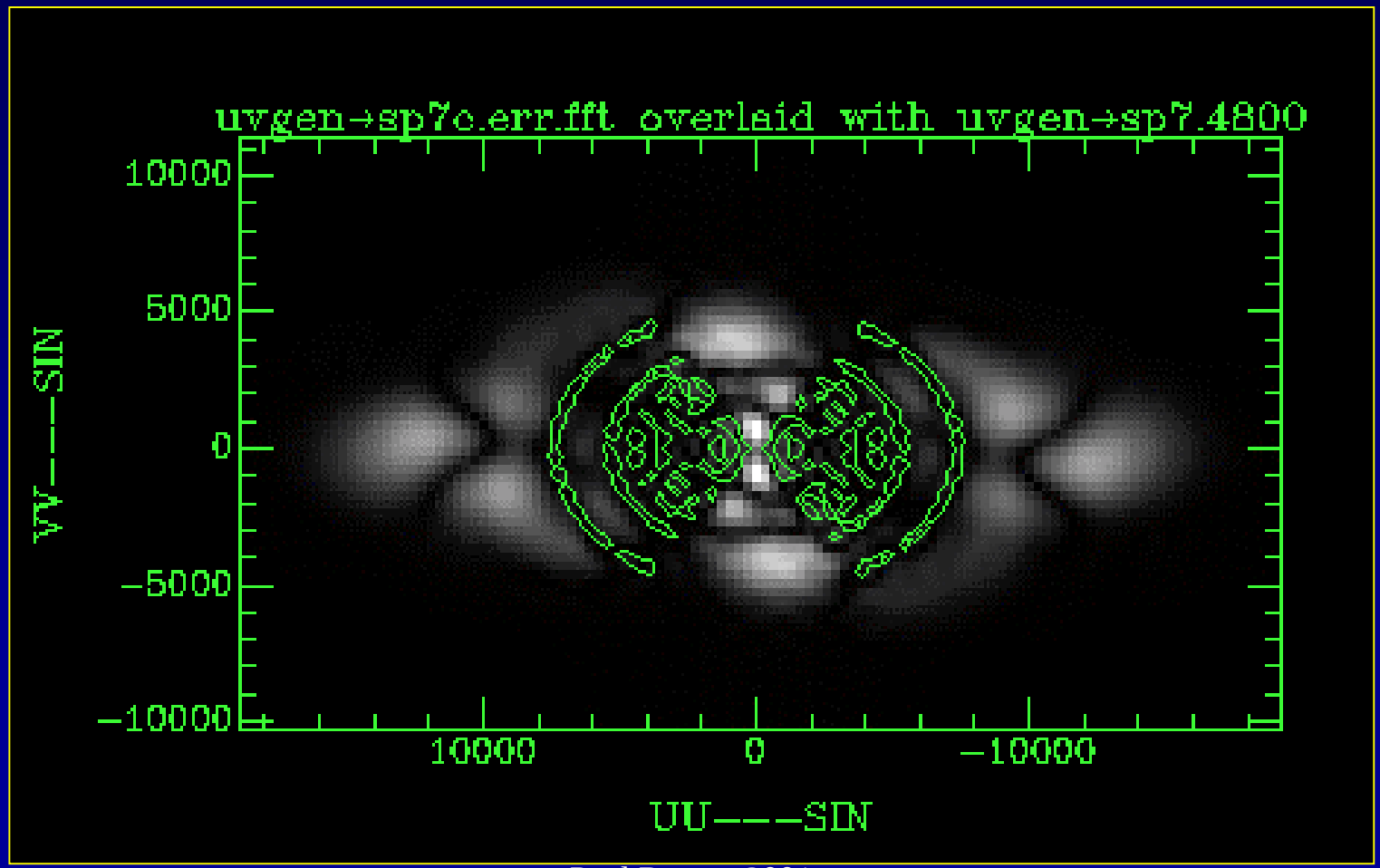
Radially Dependent Errors

- not expressible as simple operations in image/*uv* plane
  - –sometimes convertible to standard form via coordinate change
- smearing effects
  - –bandwidth: radial - like coadding images scaled by frequency
  - –time-average: tangential – baselines rotated in *uv* plane
- baseline, shadowing
- pointing
  - –dependent on source position in the field
  - –polarization effects worse (e.g. beam squint)

CLEAN Errors in the Image:



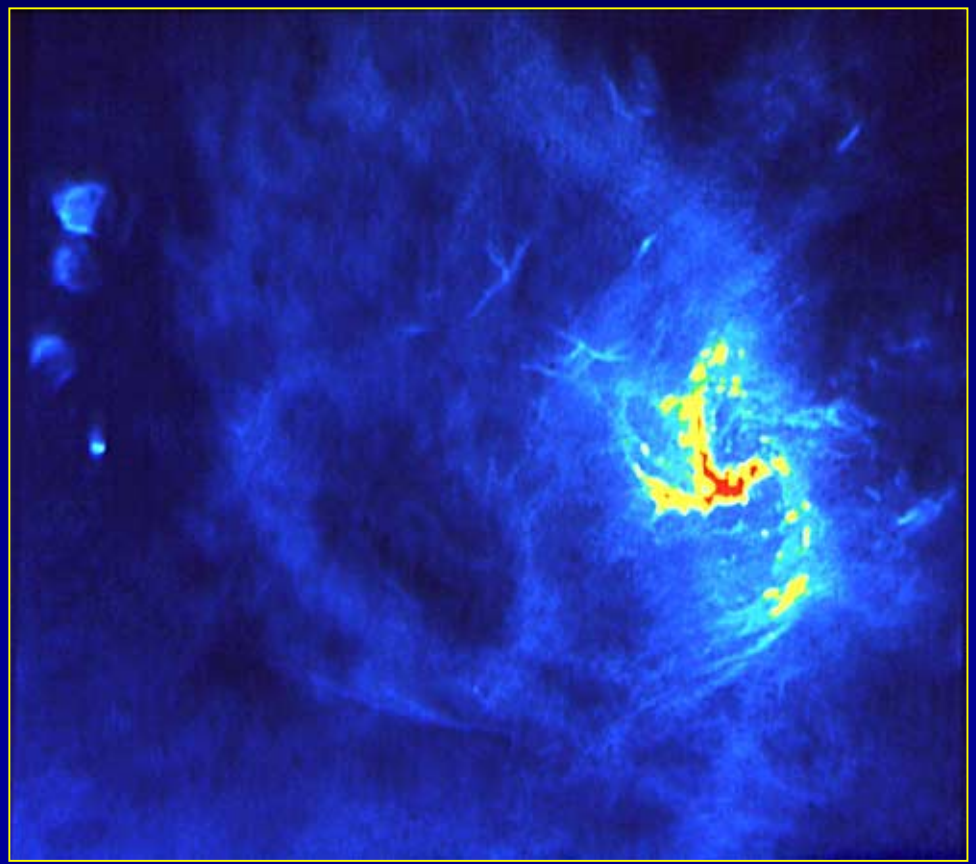
CLEAN errors in UV-plane:



Diagnostics

- Good image display
  - Negativity
  - Complex numbers
- Polarization
- Low resolution image of large field
- Source subtraction
- Fourier transform
- Statistics

Galactic Centre



- VLA 6cm
- Big picture missed by first observers
- Too much resolution too small FOV